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Influence of the tectosphere upon plate motion

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Abstract. This paper tests two hypotheses for the influence of thick lithosphere (the tectosphere) upon plate motion. The first is that the tectosphere reaches down into high-viscosity regions of the asthenosphere, effectively slowing the motion of continental plates. The second is that the tectosphere reaches down below the slow-moving convective boundary layer into regions of rapid mantle convection and effectively speeds (or slows) the motion of continental plates. Our data imply that the tectosphere speeds plate motion rather than impedes plate motion and are thus most consistent with the second hypothesis.

Introduction

The mechanical coupling between the asthenosphere and the lithosphere is one of the forces which drives plate tectonics. This coupling has been termed the "mantle drag" force by *Forsyth and Uyeda* [1975], who found that this force was small compared to other forces and that mantle drag tends to resist, rather than assist, plate motion. Their analysis, however, did not include the effect of variations in lithospheric thickness, which substantially complicate the simple picture of the asthenosphere being dragged along by an overlying, rapidly moving plate.

If the base of a plate has little or no relief and the plate is driven by boundary forces such as slab pull, then the asthenosphere will move most quickly near the base of the plate (the plate moves the mantle). If, however, a plate is driven by internal buoyancy forces, the asthenosphere will move most rapidly at some depth within the mantle (the mantle moves the plate). In either case, lithospheric thickness variations can affect the motion of a plate by varying its interaction with the asthenosphere.

Of course, both types of forces move the plates: boundary forces as exemplified in slab pull and buoyancy forces as exemplified in ridge push; however, in most plates with attached slabs, the effects of boundary forces greatly overwhelm the effects of buoyancy forces, and it is difficult to resolve the component of buoyancy-driven flow. Continental plates with no attached slab therefore provide the best opportunity to examine the role of buoyancy forces in driving plate motions. In this paper, we examine the effects of thick cratonic keels upon plate motion and use our results to make inferences about the nature of buoyancy-driven flow in the mantle. Depending upon the depth of the keel, it may either intersect a region of horizontal convective counterflow, or it may remain within the region where all horizontal mantle flow is in the upper half of the convection cell. In the former case, plate motion is impeded by the keel, while in the latter, the keel will assist plate motion.

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As we are using plate velocities to help assess the nature of lithosphere/asthenosphere interaction, it is important to review some basic assumptions and observations regarding these motions. It is currently believed by most researchers that plates, especially oceanic ones, represent the upper part of large-scale mantle convection cells. As such, they may move over, and drag, an otherwise stationary asthenosphere. This may not hold for continental plates, however, which is one hypothesis this study shall test.

All plate motions are taken relative to the hotspot reference frame [*Gripp and Gordon*, 1990], as this provides the most complete, self-consistent data set for plate motions. An underlying assumption is that such absolute plate motions also represent motion with respect to the asthenosphere; that is, that the asthenosphere is not moving in the hotspot frame. It is also important to remember that there are biases in plate motion; for instance, boundaries tend to be slow-moving, as fast-moving boundaries are more likely to collide with others and thus are preferentially eliminated [*Solomon et al.*, 1975]. Similarly, continents tend to move more slowly, as the fast ones (such as India) collide with, and are slowed down by, slower ones (such as Eurasia) [*Solomon et al.*, 1977].

If indeed plates provide a major driving force to mantle convection as described above, then flow in the asthenosphere will be a direct result of plate motion. This flow may take one of at least two forms: layered, Couette-style flow, where asthenospheric flow velocity varies linearly from that of the plate to zero at the base of the asthenosphere or, if the asthenosphere is confined to a channel, then some form of return flow at the lower part of that channel is necessary. Also, *Phipps Morgan and Smith* [1992] have proposed pressure-induced flow in the asthenosphere, due to the varying depths of the base of the lithosphere. In any of these cases, the interaction between tectospheric keels and the asthenosphere will be affected by how deeply and sharply into the asthenosphere the keel penetrates.

Tectosphere: Thickness and Age

The term "tectosphere," which formerly applied to all continental lithosphere, more recently has been restricted to the seismically fast, cold (meaning that diamond is stable), and thick

(>200-400 km) continental lithosphere [*Jordan*, 1975, 1978; *Lerner-Lam and Jordan*, 1987]. Although earlier seismic studies concluded that the tectosphere was 300 to 400 km thick, more recent, higher resolution seismic tomography suggests that most of the tectosphere is less than 300 km thick [*Zhang and Tanimoto*, 1993]. Some geochemical data also constrain the maximum thickness of the tectosphere. Despite much careful study, stishovite has never been found in mantle xenoliths from diamondiferous kimberlites and lamproites (N. Sobolev, oral communication, 1992). Stishovite is stable at pressures above ~100 kbar, and its presence would imply that a mantle xenolith came from below ~300 km depth; therefore geochemical and geophysical data both imply that the bulk of the tectosphere is less than 300 km thick.

Most of the exposed crustal basement overlying the tectosphere is Archean (>2.5 Ga); however, most of the unexposed basement and some exposed basement overlying the tectosphere are Early Proterozoic [*Hoffman*, 1990]. Examples of Early Proterozoic basement underlain by diamondiferous tectosphere occur in northern central Australia, the Birrimian of west Africa, and the Central Plains-Colorado province in North America [*Choubert et al.*, 1976; *Nixon*, 1987a; *Taylor et al.*, 1992]. The youngest known crust underlain by tectosphere (as defined by diamond stability) has been dated at 1.6 to 1.9 Ga using lower crustal zircons [*Reichenbach and Parrish*, 1988].

We know that the tectospheric mantle is also ancient. Diamond placers are found within the 2.6 Ga Witwatersrand formation [*Nisbet*, 1987] on the Kaapvaal craton in South Africa. Because the diamond-bearing rocks needed time for uplift and erosion, this observation provides a minimum age for diamond-bearing mantle beneath the South African craton. Harzburgitic inclusions in diamonds from the lithospheric mantle of the Kaapvaal craton yield model ages of 3.1 to 3.4 Ga [*Richardson et al.*, 1984]. These ages imply that the Kaapvaal craton has been cold enough and thick enough to stabilize diamonds since the Archean. From thermal considerations, we estimate that overall lithospheric thickness must exceed 200 to 220 km if diamond is to remain stable [*Abbott*, 1991].

The geologic picture of a thick, depleted lithospheric mantle root which has been stable since the Archean is complicated by geochronologic evidence for later modification of that mantle. Lherzolitic and eclogitic inclusions in diamonds from the same location as the dated harzburgitic inclusions, for example, the Premier kimberlite pipe, give successively younger ages, 1.93 Ga and 1.15 Ga, respectively [*Richardson*, 1986; *Richardson et al.*, 1993]. The age progression in the diamond inclusions mirrors the ease of melting of the mantle. The oldest ages are from harzburgitic inclusions, which are the most refractory and difficult to melt. The youngest ages are from eclogitic inclusions, which are the least refractory and difficult to melt. We suggest that the younger ages are from later metasomatic and/or reheating events and do not necessarily represent the original age of the lithospheric root; therefore the ages of diamond inclusions are in substantial agreement with the ages of the overlying crust in cratonic areas. We consequently infer that the youngest areas of thick lithosphere formed at around 1.6 to 1.9 Ga.

The data from crustal geochronology and diamond inclusion geochronology both support an ancient origin for thick lithospheric mantle, with the youngest areas of thick lithosphere being overlain by crust which is 1.6 to 1.9 Ga in age. The limited geochronologic data which are available from diamond inclusions imply that the lithospheric root has the same age as the oldest overlying crust to within several hundred million years. For this reason, we have used the age of the basement as one of our primary tools in identifying probable tectospheric mantle.

Geochemical and Thermal Characteristics of the Tectosphere

Because diffusion is the major form of heat transport in the lithosphere, the equilibrium geotherm is controlled by lithospheric thickness, lithospheric heat production, and basal (asthenospheric) temperature. Mantle heat production is relatively small, so unusually low mantle geotherms are typically associated with unusually thick lithosphere. For this reason, areas of tectosphere generally have very low heat flow; however, low heat flow has many other causes, such as downward flow of water. Therefore low heat flow is characteristic but not diagnostic of the presence of a thick lithospheric root.

In addition to its great thickness and low thermal gradients, the tectospheric mantle is also more refractory than the surrounding asthenospheric mantle [*Boyd et al.*, 1985]. The tectospheric mantle appears to be the residue of high degrees of partial melting, in most cases enough to produce rocks of basaltic komatiitic to komatiitic composition [*Boyd*, 1987]. The refractory composition of the tectosphere and the low thermal gradients within the tectosphere both impede melting. In addition, the thick lithosphere produces a shorter asthenospheric melting column. The net result is characteristic magmas that are low-degree partial melts [*Plank and Langmuir*, 1992], for example, kimberlites, olivine lamproites, and some carbonatites.

In order to remain stable, diamonds require low geotherms and thick lithosphere. Therefore all of the rocks with diamond deposits are low-degree partial melts: olivine lamproites, kimberlites, and monchiquites. In contrast, thin lithosphere has a longer melting column in the asthenosphere and is less refractory. Thin lithosphere is therefore associated with alkaline rocks derived from high percentages of partial melting, most commonly alkali basalt.

In order to determine which of our competing models best explains the observations on the effect of thick lithosphere on plate motions, we have assembled data on the global extent of thick lithosphere. We compiled data on crustal age, heat flow, the distribution of alkaline rock types and diamondiferous pipes, and the seismic characteristics of different areas to determine the possible global extent of the tectosphere.

The results of our compilation are shown in Figure 1, a map of the Earth's surface. We did not find any areas of tectosphere with basement ages younger than 1.6 Ga. We did find some areas with basement ages between 1.6 and 2.0 Ga that lacked underlying tectosphere.

Thickness of Archean and Early Proterozoic Continental Lithosphere

Recent seismic measurements of lithospheric thickness suggest that tectosphere of early Proterozoic age is thinner than tectosphere of Archean age [*Beghoul and Mereu*, 1992]. The overall pattern of lithospheric thickness in the detailed tomographic models also suggests that Archean age lithosphere is thicker than early Proterozoic age lithosphere. The tomographic models have some resolution problems, which produce problems with identification of thick lithosphere immediately adja-

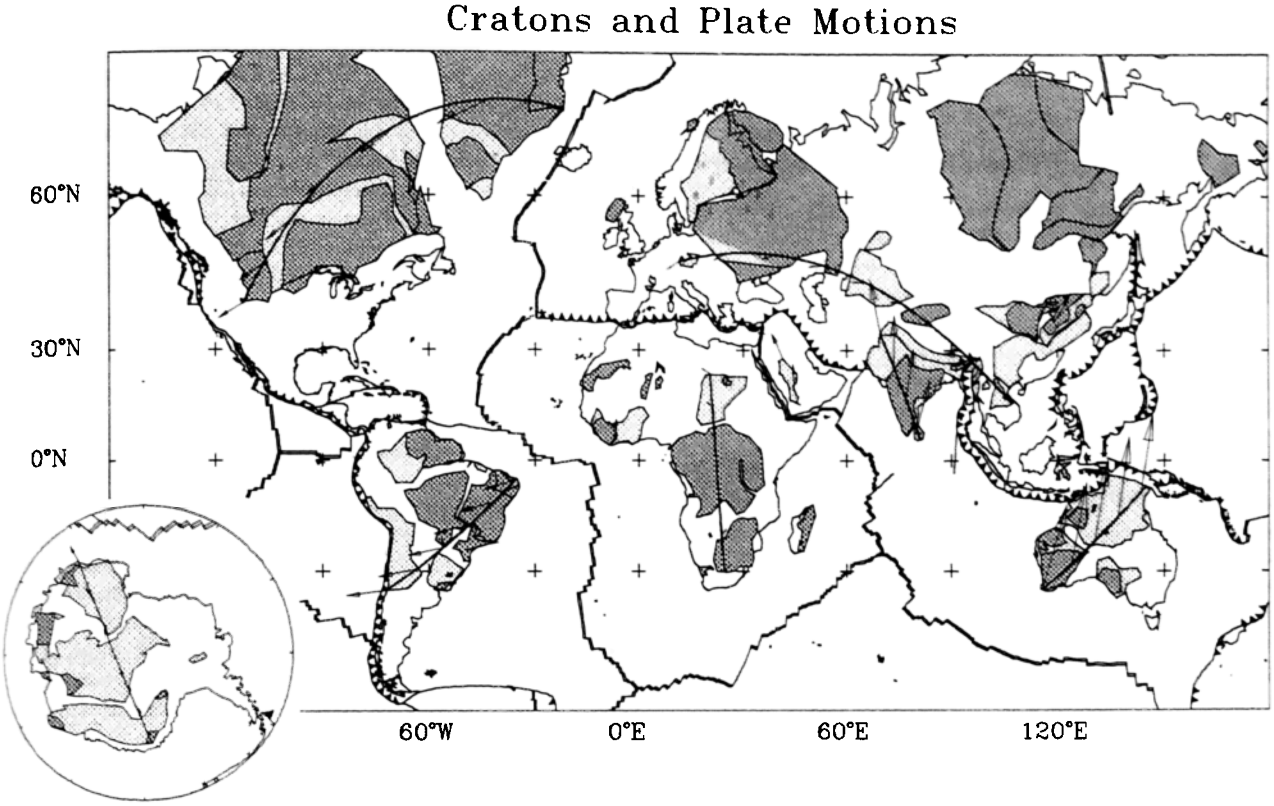

Figure 1. The global distribution of Archean and Early Proterozoic cratons with cratonal geodesics and directions of absolute plate motion. Darkest shading indicates Archean crust overlying tectosphere; medium shading indicates Early Proterozoic crust older than 1.6 Ga overlying tectosphere; and lightest shading indicates younger crust, not underlain by tectosphere. Heavy lines and arcs indicate largest great circles (geodesics) contained by each plate's tectospheric area. Arrows indicate directions and magnitudes of absolute plate motion along each geodesic. Plate boundaries are indicated by barbed lines (convergent), double lines (divergent), and single lines (transform).

cent to a hotspot. Away from major hotspots, however, there is a clear pattern of larger velocity anomalies at 210 and 310 km in areas of Archean age lithosphere than in areas of Early Proterozoic age lithosphere. This pattern in the size and distribution of velocity anomalies is consistent with thicker Archean age lithosphere rather than Early Proterozoic age lithosphere.

Three other lines of evidence also suggest that Early Proterozoic age tectosphere is on average somewhat thinner than Archean age tectosphere. First, it appears that tectosphere formation gradually ceased during the latter part of the Early Proterozoic [*Abbott et al.*, 1994]. Therefore whatever mechanism formed the tectosphere was less active during the Early Proterozoic and may have produced somewhat thinner tectosphere. Second, Archean crust has lower mean surface heat flow than Early Proterozoic crust with tectospheric mantle [*Chapman and Pollack*, 1977]. Although the effect of crustal heat production is not removed from the mean heat flow, the lower heat flow in Archean areas is most likely the result of a somewhat thicker Archean age tectosphere. Third, the observation that Archean cratons are relatively more exposed than Early Proterozoic cratons (in areas with no tectonic activity in ~300 million years) suggests that Early Proterozoic cratons are thinner than Archean cratons. Assuming that asthenospheric highs and lows average out over the total surface area of the continents, the average degree of exposure of the cratonic basement is controlled by two factors: the thickness of the crust and the thickness of the cratonic root. Because the crust is much lighter than the mantle, areas with thicker crust should, on average, have a higher elevation. From reliable seismic refraction data [*Durrheim and Mooney*, 1991; *Abbott and Mooney*, 1995], the mean crustal thickness of Archean basement is 40 ± 7 km, and the mean crustal thickness of early Proterozoic basement is 43 ± 8 km. This means that the mean crustal thicknesses on Archean and Early Proterozoic cratons are not significantly different. Archean cratons therefore cannot have a higher elevation which is the result of an increased crustal thickness. (If anything, Early Proterozoic cratons have a slightly higher crustal thickness and hence would be expected to have a higher elevation).

The second factor which can increase the elevation of the continents is an increased thickness of the buoyant lithospheric root. Below the depth at which garnet becomes stable (~80 km), the tectospheric mantle is buoyant because it has less garnet than does the asthenospheric mantle [*Oxburgh and Parmentier*, 1977]. This buoyant root acts like the root of an iceberg, producing a small amount of increased elevation above sea level for a relatively large increase in total thickness of the root. Therefore stable, cratonic areas with more tectospheric mantle below 80 km will have slightly higher elevations than stable areas with less tectospheric mantle below 80 km. Globally, this is what is observed. Stable areas with Archean crust (shields) are better exposed than stable areas with Early Proterozoic crust (platforms). Since this increased exposure is not the result of an increased crustal thickness within Archean cratons, it must be the result of a thicker tectospheric mantle beneath the Archean crust as compared to the Early Proterozoic crust [*Hoffman*, 1990].

Thick Tectosphere-Thin Lithosphere Boundaries

The abruptness of the boundary between thick tectospheric continental lithosphere (200-400 km), and the thinner continental lithosphere (80-125 km) is important because a steep, short boundary zone could enhance viscous interaction between the convecting asthenosphere and the plate. A rapid transition from thin lithosphere to thick lithosphere would present a steeper face to the asthenosphere and thus would be more likely to increase the coupling between the moving asthenosphere and the plate.

Until recently, most seismic data on the tectosphere were derived from global seismic networks, and there was poor resolution of the edge of the tectosphere; however, there are now many more detailed tomographic data which support an abrupt transition from thick to thin lithosphere. A tomographic cross section of Lake Baikal shows the edge of the tectosphere as a steep interface [*Zhang and Tanimoto*, 1993]. Given the vertical exaggeration and uncertainties of the profile, the lithosphere in the Lake Baikal area goes from 0 to 300 km thick over a distance of 500 to 1000 km, which would imply a minimum slope of 20°. On the basis of simple surface wave modeling of data from a closely spaced array, the thickness of the continental lithosphere in the Rocky Mountains varies from greater than 200-km to less than 80 km over a distance of 200 km or less [*Chen and Lerner-Lam*, 1993], which would imply a minimum slope of 31°. In the east African rift valley, we find that the dominant magmatism changes from diamond-bearing kimberlites to alkali basalts over ~200 km length scales [*Nixon*, 1987b]. These observations imply a change in lithospheric thickness from less than 100 km to at least 200 km and would imply a minimum slope of the edge of the tectosphere of ~27°; therefore there are multiple lines of geologic evidence that support an abrupt transition from thin to thick continental lithosphere. Thus interaction at the boundary could be quite strong, as this steep face either pushes through, or is pushed by, the asthenosphere.

Procedure

We digitized the Archean and Proterozoic cratonic boundaries and determined cratonic surface areas by performing line integrals around the boundaries for each of nine plates: Africa, Antarctica, Arabia, Australia, Burma, Eurasia, India, North America, and South America. With the exception of Burma, all velocities were based on NUVEL 1 Euler poles and absolute angular velocities [*Gripp and Gordon*, 1990]. For the Burma plate, for which Gripp and Gordon did not determine a pole, the absolute velocity vector was determined by adding the Burma/Eurasia relative motion vector [*Addicott and Richards*, 1983] to the NUVEL 1 Eurasia absolute vector. For each plate, linear absolute plate velocities (in kilometers per million years) were calculated for each point of a 1° grid over that plate, using the relation

$$V = |\mathbf{V}| = |\boldsymbol{\omega}\times\mathbf{R}| \qquad (1)$$

where $\boldsymbol{\omega}$ is the plate's absolute angular velocity (in the hotspot reference frame) and $\mathbf{R}$ is the point's location. The plate's average absolute velocity was found by taking the mean of all point velocities.

If the tectosphere either impedes or aids plate motion, then an additional relationship may exist between the direction of plate motion and the orientation of the tectospheric keels. We therefore calculated the angle (called $\delta\phi$) between the long axis of the craton and the direction of absolute plate motion. We calculated the azimuthal difference between the trend of the longest great circle, or geodesic, within a plate's tectospheric area and the direction of absolute plate motion. Because the direction of absolute plate motion changes along the geodesic, we made the calculation at 10-km intervals and then summed and averaged to find the mean difference (see arrows in Figure 1). In such a relation, the aspect ratios of tectospheric regions are important; therefore after finding the longest great circle path across the tectosphere, we then found the longest geodesic perpendicular to this long axis of the tectosphere. The ratio of the lengths of the two geodesics provides an estimate of the aspect ratio of the tectospheric area.

Tables 1 and 2 summarize several plate, craton, and continent parameters which have been plotted versus absolute plate velocity. The errors in plate velocity, σ_ω, were calculated using the errors given by *Gripp and Gordon* [1990] and a given plate's average distance from its Euler pole. The error (σ_{aspect}) in estimating relative orientation of plate motion versus the longest axis ($\delta\phi$) is based on the width of the cratonic keel exposed to the asthenospheric flow, with the assumption that flow is parallel to plate motion. Apparent width versus orientation graphs were integrated numerically for a range of aspect ratios, and a raw σ_{aspect} was defined for each ratio such that a distance of $\sigma_{aspect}/2$ from the center of the plot covered ~67% of the area under the curve. An example is shown for an aspect

Table 1. Craton Parameters

	Archean			Proterozoic			Total Craton				
Plate	Area, 10^6 km^2	Percentage of Plate	$\delta\phi$, deg	Area, 10^6 km^2	Percentage of Plate	$\delta\phi$, deg	Area, 10^6 km^2	Percentage of Plate	Aspect Ratio	$\delta\phi$, deg	σ_{aspect} deg
Afr	7.942	10.2	4.45	3.189	4.1	11.72	11.131	14.4	2.17	2.89	4.1
Ant	5.806	10.0	0.90	0.952	1.6	0.46	6.758	11.6	1.49	3.19	6.9
Ara	0.000	0.0	0.00	0.333	6.7	16.46	0.333	6.7	3.41	11.94	2.3
Aus	1.802	3.8	67.06	3.248	6.8	33.48	5.050	10.6	2.09	34.75	4.3
Bur	0.000	0.0	0.00	0.144	10.5	84.66	0.144	10.5	1.74	22.00	5.6
Eur	10.500	15.6	22.83	6.283	9.3	22.83	16.783	24.9	3.40	15.35	2.3
Ind	1.963	16.3	6.66	1.689	14.1	16.41	3.652	30.4	1.27	25.65	8.8
Nam	8.846	14.8	7.62	3.548	5.9	7.66	12.394	20.8	1.55	7.24	6.6
Sam	5.008	11.8	89.35	4.913	11.5	24.86	9.921	23.3	1.18	25.05	9.9

Afr, African; Ant, Antarctica; Ara, Arabian; Aus, Australian; Bur, Burma; Eur, Eurasian; Ind, Indian; Nam, North American; Sam, South American.

Table 2. Plate and Continent Parameters

	Plate				Continental Region				
Name	Absolute Velocity, km/m.y.	σ_{ω}, km/m.y.	Area, 10^6 km^2	$\delta\phi$, deg	Area, 10^6 km^2	Percentage of Plate	Aspect Ratio	$\delta\phi$, deg	σ_{aspect}, deg
Afr	8.941	2.980	77.529	6.64	21.513	27.7	1.49	3.06	6.9
Ant	10.311	8.436	58.032	86.85	10.685	18.4	1.50	24.53	6.9
Ara	28.724	2.666	4.939	24.86	3.968	80.3	1.51	45.92	6.8
Aus	75.119	6.919	47.556	86.85	7.494	15.8	1.25	23.87	9.0
Bur	34.546	7.000	1.365	68.98	0.719	52.7	5.53	87.91	1.5
Eur	9.448	9.448	67.320	17.20	39.062	58.0	1.58	15.50	6.4
Ind	48.620	4.420	12.013	24.84	4.311	35.9	1.21	19.39	9.5
Nam	20.617	5.891	59.672	59.58	23.407	39.2	1.08	30.85	11.4
Sam	33.036	8.259	42.549	42.55	10.898	25.6	1.54	71.57	6.6

Abbreviations are the same as in Table 1.

ratio of 3.5 in Figure 2a. Using this percentage of the area (67%), a plot of the raw σ_{aspect} versus aspect ratio shows that σ_{aspect} asymptotically approaches ~42° (Figure 2b). This value was subtracted from the raw σ_{aspect} to give those values listed in Tables 1 and 2 (Figure 2c).

Results

Of the nine plates with cratons, only Australia and perhaps India have significant, deeply dipping slabs, and therefore these two will be considered apart from the other plates, as slab pull appears to be the major driving force of plate movements [e.g., *Forsyth and Uyeda*, 1975; *Harper*, 1975; *Chapple and Tullis*, 1977]. Indeed, in almost all plots, Australia has an anomalously fast velocity, an observation attributable to the pull from its slab. India has been treated as a plate separate from Australia [*Wiens et al.*, 1985; *DeMets et al.*, 1988; *Gordon et al.*, 1990; *Royer and Chang*, 1991; *Gordon and Stein*, 1992]. Because India is faster than the remaining plates, but not significantly so, it can be argued that India's slab may have detached or has heated up and lost some of its negative buoyancy; however, evidence for this is still far from compelling. The question of India's slab will be addressed from a statistical standpoint. North Africa has a small, shallowly dipping slab, while the remaining plates have either minuscule slabs or none at all.

In Figures 3a-e, total cratonic, continental, and plate areas are plotted against plate velocity. With the exception of Proterozoic area (Figure 3b), and excluding the Australian plate, the overall trend in each of the plots is negative, indicating that large plates tend to move more slowly. This generally supports the idea that mantle drag typically resists plate motion, because mantle drag is proportional to plate area [e.g., *Forsyth and Uyeda*, 1975]. Australia plots well above this trend, indicating "excess" velocity, which is probably due to the attached downgoing slab. For Figure 3e (plate area vs. plate velocity), the linear correlation coefficient r is -0.87, which corresponds to a 94.5% probability that velocity and area are related. For comparison, the correlation of velocity and effective ridge length (as defined in *Forsyth and Uyeda* [1975]) yields a value for r of -0.41 and a probability P_r of 37%, indicating that velocity correlates more closely to plate size than to effective ridge push. Equivalent plots for continental and cratonic regions (Figures 3a, c, d) display similar results, indicating only that larger plates tend to have larger continental and cratonic areas.

To gain some insight into any correlation between continent and craton size and plate motion, we normailized Proterozoic, Archean and total craton areas, as well as continental area, to plate size (Figures 4a-4d). Only the Proterozoic showed any significant correlation. Perhaps contrary to intuition, plates with a large percentage of Proterozoic cratons tend to move fast, suggesting that, unlike mantle drag at the base of thin

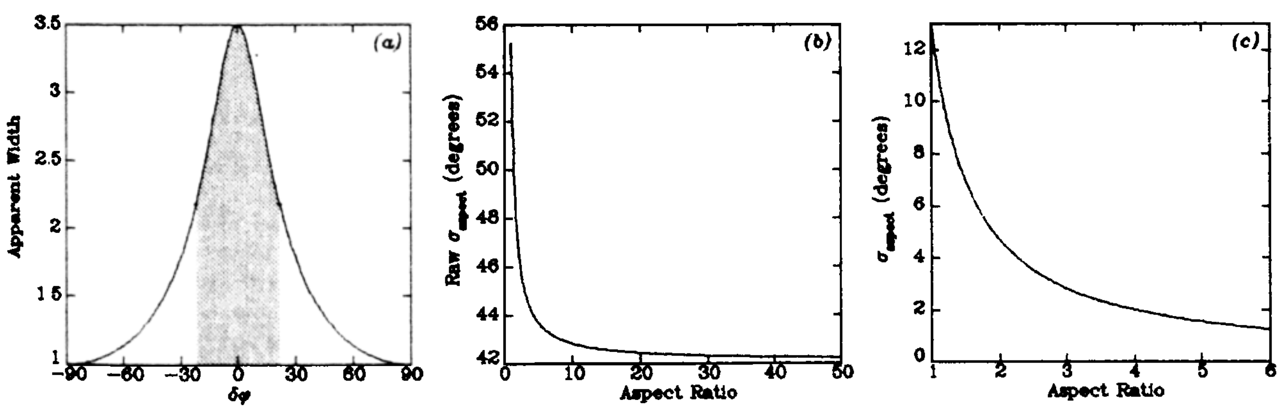

Figure 2. Determination of errors associated with $\delta\phi$, the difference between direction of plate motion and the long axis of the craton, as a function of aspect ratio. (a) Example for an area with an aspect ratio of 3.5 is shown. Shaded region is ~67% of area under the curve. (b) Raw σ_{aspect} versus aspect ratios ranging from 1 to 50 is shown. Curve asymptotically approaches ~42°. (c) Resulting σ_{aspect} versus aspect ratios ranging from 1 to 6 is shown, after subtraction of asymptotic limit.

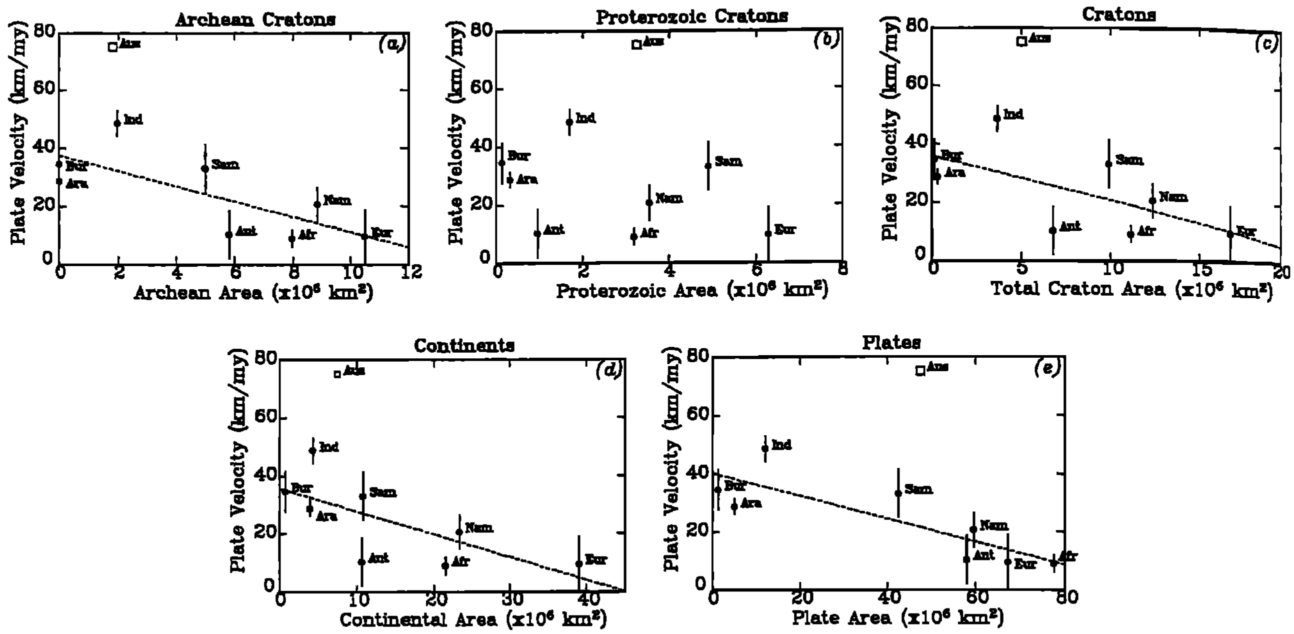

Figure 3. Area versus absolute plate velocity. Open symbols indicate points not used in calculating trends (dashed lines) and correlation coefficients, but which are shown for comparison's sake. Trend lines are shown when the correlation coefficient is greater than 0.5. See text for discussion of error bars. (a) Archean area versus plate velocity is shown. (b) Proterozoic area versus plate velocity is shown. (c) Total cratonic area versus plate velocity is shown. (d) Continental area versus plate velocity is shown. (e) Plate area versus plate velocity is shown. Plate abbreviations: Afr, African; Ant, Antarctica; Ara, Arabian; Aus, Australian; Bur, Burma; Eur, Eurasian; Ind, Indian; Nam, North American; Sam, South American.

lithosphere, deep keels assist plate motion. A layered asthenospheric flow may be necessary to explain these conflicting observations. In such a system, the asthenosphere near the base of the lithosphere has a lower velocity, while the flow at depths corresponding to those of the Proterozoic tectosphere is faster. This type of flow is characteristic of buoyancy-driven mantle convection. The lack of any significant correlation between Archean area and plate velocity (Figure 4a) indicates that any asthenospheric flow which assists plate motion does not extend beyond the base of the Proterozoic roots. Alternatively, as no

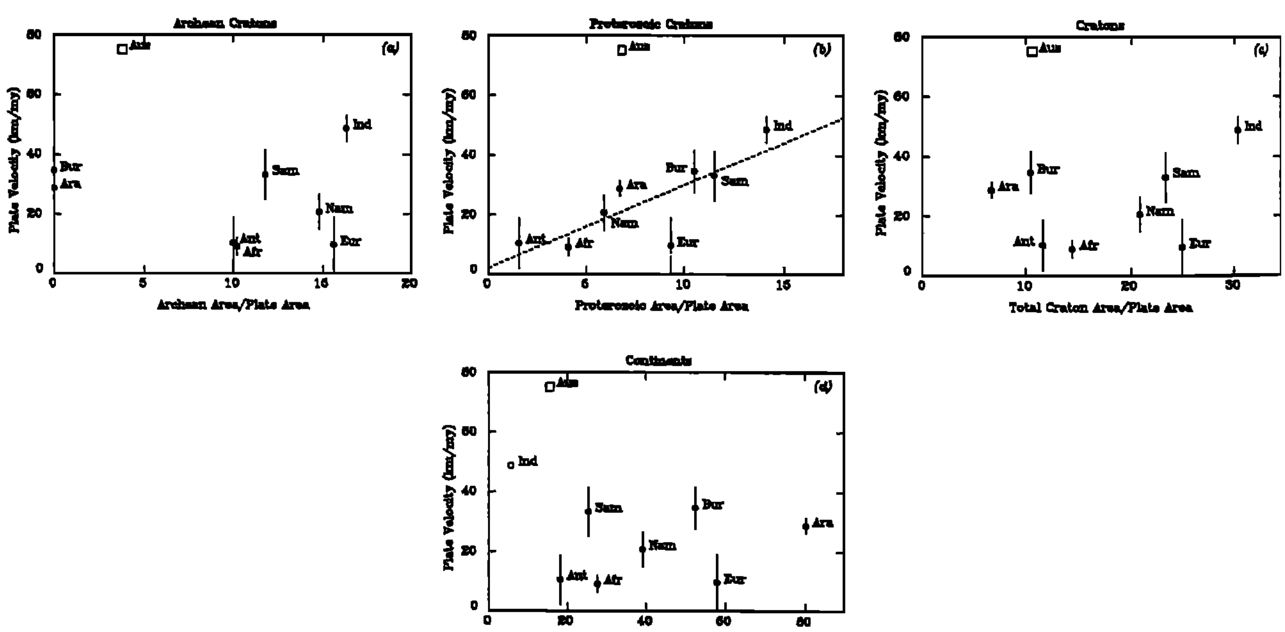

Figure 4. Normalized area versus absolute plate velocity. Areas normalized to corresponding plate area are shown. Symbols and abbreviations are the same as in Figure 3. (a) Normalized Archean area versus plate velocity is shown. (b) Normalized Proterozoic area versus plate velocity is shown. (c) Normalized total cratonic area versus plate velocity is shown. (d) Normalized continental area versus plate velocity is shown.

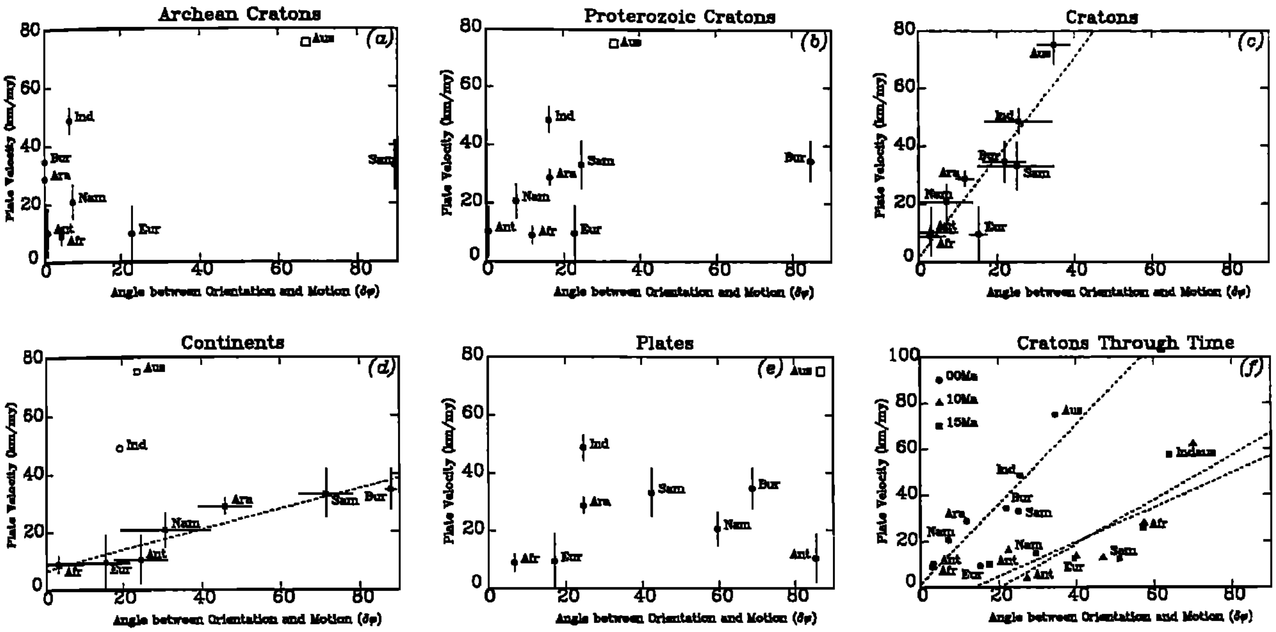

Figure 5. Angle between craton orientation (craton long axis) and direction of plate motion ($\delta\phi$) versus absolute plate velocity. Error bars for $\delta\phi$ represent σ_{aspect}. Symbols and abbreviations are the same as in Figure 3. Shown are (a) Archean cratons, (b) Proterozoic cratons, (c) cratons, (d) continents, (e) plates, and (f) cratons at 0 Ma (circles), 10 Ma (triangles), and 15 Ma (squares).

other regions display this behavior, it is possible that this correlation has no physical significance, keeping in mind that 1 in 20 plots of random data should have a confidence interval of 95%; however, as Figure 3b (plate velocity vs. Proterozoic area) is the only velocity versus area plot that shows no significant correlation, there may indeed be a relation between asthenospheric flow and the Proterozoic roots.

We also tested for a possible relationship between plate velocity and craton orientation and, for comparison, plate and continent orientation (Figures 5a-5e). If indeed the tectosphere is affecting plate motion, its orientation should be affected by the relative motion in the underlying asthenosphere. Assuming that the asthenosphere is fixed, the relative motion between the lithosphere and asthenosphere is given by absolute plate motion. In Figure 5, the difference ($\delta\phi$) between the direction of absolute plate motion and the trend of the longest axis of the craton is plotted against plate velocity. No correlation is apparent for the individual cratonic regions (Archean and Proterozoic, Figures 5a and 5b) or for the plates (Figure 5e); however, the plot for the entire cratonic region (Figure 5c) shows a strong, positive correlation ($r = 0.84$), which may include Australia. By excluding Eurasia, which has a very complex cratonic keel that therefore may not act as the other keels, we found a value of 0.94 for the linear correlation coefficient. Whether or not Eurasia is excluded, however, this correlation strongly suggests some form of interaction between the asthenosphere and the tectospheric keels.

It is also interesting to note that no plates have keels oriented more than 45° to the direction of motion. The chance for this being a purely random occurrence for nine plates is the same as for a flipped coin coming up heads or tails nine consecutive times, or one in 256. This strongly suggests that there is a real correlation between direction of craton orientation and plate motion.

There is also an apparent correlation between continental orientation and plate velocity (Figure 5d). The slope of the best fit line is less than that for craton orientation, suggesting that the effective coupling of the asthenosphere to the continental lithosphere is less than that to the tectosphere. It must be pointed out, however, that this correlation does not include the Indian plate, which would be appropriate only if India's slab has not detached from the rest of the plate. In contrast, a comparison of plate orientation to plate velocity shows no correlation (Figure 5e, $r = 0.11$), further supporting the importance of coupling of the asthenosphere to the tectosphere and, to a lesser extent, to the "normal" continental lithosphere.

Plates with cratons and continents oriented nearly parallel to motion move more slowly than those with tectospheric keels at higher angles to motion, supporting the idea that lower asthenospheric flow is pushing the keels and consequently, the lithosphere, in the direction of plate motion. The strong positive correlation of craton orientation with plate velocity argues against a major role for mantle viscosity variation. If mantle viscosity variations were the most important variable, the long axes of the cratons would tend to be oriented parallel to the directions of the absolute plate motions.

Reconstruction Results

The strong correlation between velocity and cratonic $\delta\phi$ for the present-day plate configuration suggests that this relation should hold for past configurations as well. Using the poles given in *Gordon and Jurdy* [1986], reconstructions were made for a suite of ages from 10 Ma to 64 Ma, including ages of stable plate motion and ages of reconfigurations. For each reconstruction, plate velocities and craton orientations were computed and compared. Only those comparisons for the most recent times (10 Ma and 15 Ma) showed significant correlations (Figure 5f), and those showed a different trend than the correlation for the present.

The lack of correlation for older times may be due to problems finding accurate reconstruction poles, with the poles for the older times being less well constrained. In addition, the assumption of a fixed hotspot frame may break down for times older than 20 Ma [*Jurdy and Stefanick*, 1987]. Alternatively, one may view all reconstructions skeptically, as the reconstruction poles for the most recent time interval (typically 10-0 Ma) given by numerous authors [*Gordon and Jurdy*, 1986; *Engebretson et al.*, 1985; *Duncan and Richards*, 1991] differ significantly from the NUVEL 1 instantaneous poles of *Gripp and Gordon* [1990], which are based on the largest amount of data.

Indian Slab

Given the limited data set, we have used bootstrap statistics to help determine whether India is better counted among the plates without slabs or with Australia, whose slab is adding a considerable driving force and is thus responsible for the high velocity of the plate. Briefly stated, bootstrapping involves the grouping of individual data points, in all possible combinations, to test the significance of any single point, or any group of points, to the correlation. In only one instance, that of continental $\delta\phi$ (Figure 5d), did exclusion of the Indian plate appreciably improve the correlation, from $r = 0.5$ to $r = 0.94$. While this is a sizable jump in the linear correlation coefficient, it only represents a 12% improvement in bootstrap confidence (85%, compared to 73%), while the exclusion of Australia alone increases r from 0.17 to 0.5 and the bootstrap confidence limit from 37% to 73%. If, however, India truly does behave differently from the nonslab plates in this instance, it may indicate that the influence of continental orientation is weak compared to that of the cratonic keels and the direction of India and Australia plate motion is determined more by the subducting slab.

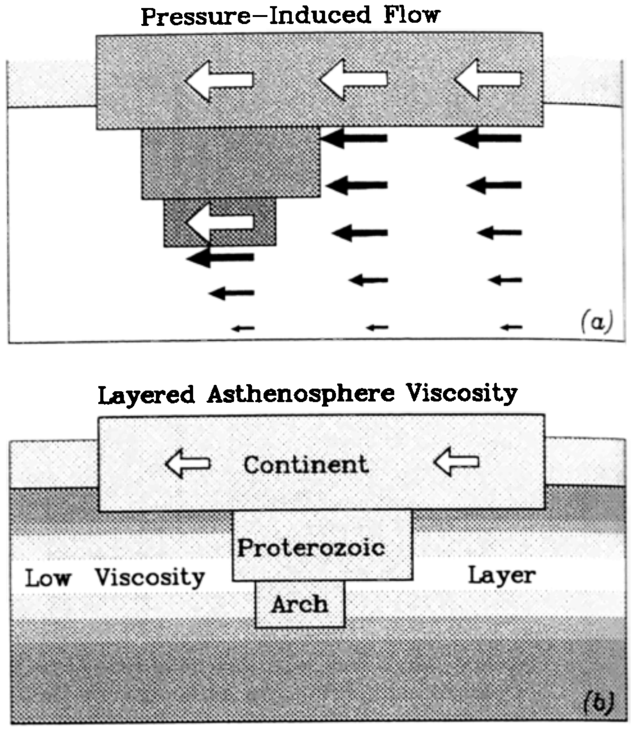

Figure 6. Schematic models of asthenosphere/lithosphere interaction. (a) Pressure-induced flow is shown. White arrows indicate lithospheric velocity; black arrows indicate asthenospheric velocity, assuming viscous shear and Couette flow. Note that arrows in central column are larger than those to the right thus providing an additional driving force at the tectospheric keel. (b) Viscosity-layered asthenosphere, assuming lowest viscosity at depths corresponding to that of Proterozoic cratons, is shown.

Discussion

Several interesting suggestions can be made from this relatively simple study, pertaining not only to lithospheric keels, but also to the slab pull and mantle drag forces.

Two results of this study confirm those of previous works: (1) For plates without slabs, mantle drag may be significant and clearly acts against plate motion and (2) Australia apparently is being driven in large part by its attached downgoing slab, as it moves significantly faster than the other continental plates. In most comparisons, bootstrap analysis showed that India's velocity is more similar to that of the other continental plates, suggesting that India's slab may have lost its negative buoyancy because of heating by the surrounding mantle.

Results regarding lithospheric keels, however, are more intriguing. Two correlations suggest that asthenospheric flow at the level of the Early Proterozoic tectosphere acts to help plate motion: plates with larger cratons move faster and plates with cratons oriented at higher angles to directions of absolute motion move faster. In addition, Archean tectospheric mantle does not appear to aid or hinder plate motion, implying that asthenospheric motion below the base of the Proterozoic age tectosphere has a neutral effect upon plate motion. Two qualitative models, consistent with the hypothesis that asthenospheric drag tends to hinder motion, could explain these observations.

One model is a pressure-induced flow within the asthenosphere (Figure 6a), similar to that postulated by *Phipps Morgan and Smith* [1992]. In this model, viscous coupling between the base of the lithosphere and asthenosphere leads to a steeper velocity gradient under keel regions. This, in turn, leads to a lateral gradient at depths comparable to the keels themselves, resulting in a net asthenospheric "push" on the keels (middle row of black arrows in Figure 6a). The steeper velocity gradient under the keels requires, however, more resistance to motion; thus negating (at least in part) the benefit of the push for Archean regions.

A second model assumes a viscosity-layered asthenosphere (Figure 6b). Here rather than providing an additional driving force, a low viscosity layer of the asthenosphere, again at depths comparable to the keels, allows for a region of relatively low resistance. Plates with more Proterozoic keel area would see relatively less resistance, whereas Archean keels, extending down into higher viscosity regions, would not greatly influence plate motion.

Future Work

The conclusions presented above should be considered only as preliminary. Simplifications were made, and more analyses will be necessary before firmer conclusions about the nature of lithosphere/asthenosphere interactions can be formed.

1. No consideration was made of the nature of plate interactions, specifically in the cases of the Burma and Indian plates, whose motions may be significantly affected by their interactions with the Eurasian plate. Also potentially affecting plate

motions is the tendency for plates to move away from newly formed ridges during continental breakup.

2. More detailed reconstruction poles would enable better comparisons of motions and trends for past times. Additionally, more detail in past plate motions, such as the recent split of North America and Greenland, may affect the trends observed here.

3. The interaction of asthenospheric flow with tectospheric keels, if significant, should create fluid pressure variations within the asthenosphere that may be detectable in the geoid.

4. The relations observed here between plate velocities and cratons are highly dependent on reference frame, which ideally should be that of the asthenosphere. The hotspot frame may not be the closest to an asthenosphere frame, especially for times prior to ~20 Ma [*Jurdy and Stefanick*, 1987]. Other reference frames, such as no-net-torque, might provide a better estimate of the asthenosphere frame. Preferable to either frame, though, would be a realistic model of global asthenospheric flow to compare to plate motions and craton orientations.

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